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Electric Vehicles in New Zealand: Technologically Challenged?

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1. INTRODUCTION

Electric vehicles (EVs) were first developed commercially in the 1890s and went on to achieve considerable popularity and market share in the early 1900s. However, they were rapidly eclipsed by internal combustion engine vehicles (ICVs), which offered better performance and greater convenience at a lower price point. Despite a later revival of interest in the 1990s due to escalating oil prices, EVs continued to be hampered by their limited range and speed [1]. Today, electric and hybrid vehicles are presented as the future of modern automotive technology, offering the possibility of cheap and efficient transportation with lower emissions. However, a number of technological barriers still exist that must be surmounted for EVs to be successful in the long-term [2].

Although EVs are mechanically simpler than equivalent ICVs, their battery packs and electric motors continue to present a significant engineering challenge for vehicle manufacturers. Current generation midrange EVs can travel up to 150 km on a single charge, require 6 to 8 hours to fully recharge a depleted battery using a Mode 1 charger, and cost approximately $60,000 in New Zealand [3, 4]. This is in direct comparison to a new ICV such as the 2013 Toyota Corolla, which can travel over 500 km on a full tank and only costs $35,000 [5].

The responsibility for developing and improving this technology largely falls to current vehicle and original equipment manufacturers (OEMs). In particular, significant research and development must be carried out by battery cell and pack manufacturers to ensure EVs become more cost effective and capable of longer driving ranges. However, due to the absence of a local vehicle manufacturing industry and limited component manufacturing opportunities in New Zealand, the long-term feasibility and potential success of EVs is largely dependent on key manufacturers in other countries [6].

Instead, the main area in which New Zealand can influence the uptake and impact of EVs is via the development of local infrastructure. Compared to other alternative fuel technologies such as hydrogen, compressed gas, and biofuel vehicles, EVs benefit from having a pre-existing and well-established ‘refuelling’ infrastructure in the form of the national grid. However, consideration must still be given to the construction and availability of public charging stations; potential recharging rates and consequent power demands; and the integration of such devices with current infrastructure and new smart services.

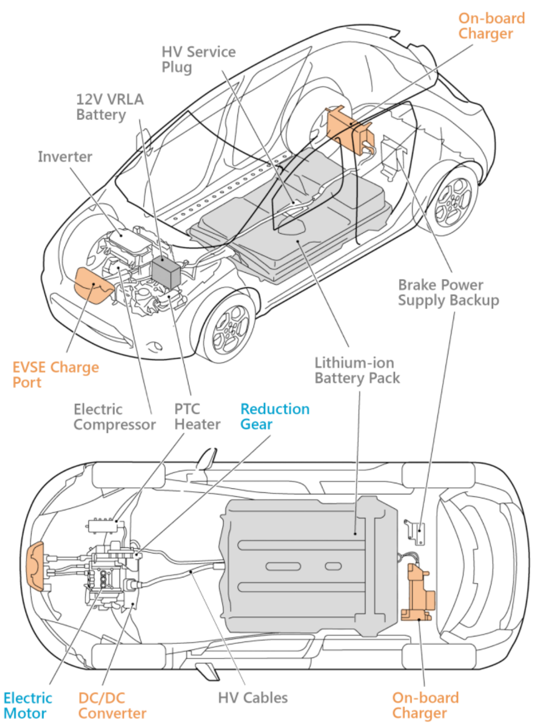
Subsequently, this paper aims to provide an overview of current and future electric vehicle technology by examining three key areas. This includes the architecture and key components of modern electric vehicles; the manufacturers producing these vehicles and components; and the infrastructure required to support the integration of electric vehicles into the national fleet.

2. ELECTRIC VEHICLE ARCHITECTURE

Electric vehicles can be divided into three main types: hybrid electric vehicles (HEVs), pluggable hybrid electric vehicles (PHEVs) and full electric vehicles (FEVs/BEVs/EVs). Hybrid electric vehicles retain the internal combustion engine and drive, while also incorporating a small battery and electric drive motor. While the higher efficiency of the electric drive and the capacity for regenerative breaking results in decreased fuel consumption, the vehicle cannot be powered by electricity alone and still relies on petrol or diesel [7].

PHEVs extend the concept of a full HEV by increasing the size of both the battery and electric motor, as well as allowing it to be charged externally from a power source. Consequently, the vehicle can be driven over short ranges where it only consumes electricity from the battery. However, beyond a defined level of battery consumption the vehicle reverts back to using the internal combustion engine alongside the electric motor like a standard hybrid [8].

Full EVs are generally mechanically less complex than both internal combustion and hybrid vehicles, as shown in Fig. 1. By replacing the fuel tank with a high energy density battery and the internal combustion engine with an efficient electric motor, EVs are capable of achieving significant efficiency improvements and emission reductions. Their range, efficiency, cost and torque-speed characteristics are predominantly determined by their battery pack and electric motor(s). Consequently, these components vary significantly between EVs depending on the desired performance and target market, as shown in Table 1.



Component	Description
Electric Motor	Permanent magnet synchronous motor powered by three-phase AC from the inverter that supplies torque to the transaxle
Li-ion Battery	High specific energy electrochemical supply for powering the vehicle during operation
Reduction Gear	Steps down motor speed and increases torque
Inverter	Converts DC power from li-ion battery to three-phase AC power for controlling the motor
HV Junction Box	Interfaces the li-ion battery with high-voltage systems
Electric Compressor	Compressor for cabin air conditioning
PTC Heater	Positive temperature coefficient heat source for the interior cabin
Charge Ports	Standard connection ports for interfacing with EVSE to recharge the battery
On-board Charger	Converts AC power supplied to the standard charge port into DC power for recharging the battery
DC/DC Converter	Steps down the HV li-ion supply to recharge 12 V VRLA battery
VRLA Battery	12 V valve-regulated lead-acid battery that powers the low voltage systems: headlights, audio, display
HV Cables	High rated conductors for carrying DC current between battery and HV systems
Service Plug	Allows the HV systems to be manually disconnected from the battery
Power Supply Backup	Capacitor-based power system that supplies power to the brakes and emergency systems if 12 V battery fails

Figure 1. A diagram of a Nissan Leaf, showing the key functional components typical to an EV [9].

Vehicle Model	Type	Motor (kW)	Motor Type	Battery (kWh)	Battery Chemistry	Battery Supplier
Audi A3 e-tron	EV	20	AC PMSM	26.5	Lithium manganese spinel	-
Audi e-tron Spyder	PHEV	30	AC PMSM	9.1	Lithium manganese spinel	-
BMW ActiveE	EV	125	AC HSM	32	Lithium nickel manganese cobalt	SB-Limotive
BMW i3	EV	130	AC HSM	22	Lithium nickel manganese cobalt	SB-Limotive
Bollore Bluecar	EV	50	AC WRSM	30	Lithium vanadium oxide	Bollore Group
BYD e6	EV	75	AC PMSM	48	Lithium iron phosphate	BYD Energy
BYD S6DM	PHEV	85	AC PMSM	16	Lithium iron phosphate	BYD Energy
Chery M1EV	EV	45	AC PMSM	16	Lithium iron phosphate	China BAK Battery
Chevrolet Spark EV	EV	100	AC PMSM	20	Lithium iron phosphate	A123 Systems
Chevrolet Volt	PHEV	111	AC PMSM	16	Lithium nickel manganese cobalt	LG Chem
Citroen C-Zero	EV	47	AC PMSM	16	Lithium titanate	GS Yuasa
Coda Sedan	EV	100	AC PMSM	31	Lithium iron phosphate	LIO Energy Systems
Detroit Electric e63	EV	150	AC AFPM	25	Lithium polymer	-
Dodge Circuit EV	EV	200	BLDC	26	Lithium iron phosphate	A123 Systems
Fiat 500e	EV	83	AC PMSM	24	Lithium iron phosphate	A123 Systems
Fisker Karma	PHEV	120	AC PMSM	20	Lithium iron phosphate	A123 Systems
Ford C-Max Energi	PHEV	88	AC PMSM	7.6	Lithium nickel manganese cobalt	Magna/JCI-Saft
Ford Focus Electric	EV	107	AC PMSM	23	Lithium nickel manganese cobalt	Magna/JCI-Saft
Honda Fit EV	EV	92	AC PMSM	20	Lithium titanate	GS Yuasa
Hyundai BlueOn	EV	61	AC PMSM	16.4	Lithium polymer	LG Chem
Indica Vista EV	EV	55	AC PMSM	26.5	Lithium iron phosphate	Energy Innovation Group Ltd.
Lumeneo Neoma	EV	34	AC PMSM	14.2	Lithium nickel manganese cobalt	Dow Kokam
Lumeneo Smera	EV	30	AC PMSM	9.3	Lithium nickel manganese cobalt	Dow Kokam
Mia Electric	EV	9.7	AC PMSM	8	Lithium iron phosphate	EVida
Mitsubishi i-MiEV	EV	47	AC PMSM	16	Lithium titanate	GS Yuasa
Nissan Infiniti LE	EV	100	AC PMSM	24	Lithium nickel manganese cobalt	AESC
Nissan LEAF	EV	80	AC PMSM	24	Lithium manganese spinel	AESC
Peugeot iOn	EV	47	AC PMSM	16	Lithium titanate	GS Yuasa
Renault Fluence ZE	EV	70	AC WRSM	22	Lithium manganese spinel	AESC
Renault Zoe	EV	65	AC WRSM	22	Lithium manganese spinel	AESC
Reva L-ion/G-Wiz	EV	13	AC PMSM	9.6	Lithium manganese spinel	-
Smart Fortwo ED	EV	30	AC PMSM	15	Lithium iron phosphate	Tesla/Li Tech
Subaru G4e	EV	65	AC PMSM	-	Lithium vanadium oxide	-
Tazzari Zero	EV	15	AC IM	12.3	Lithium iron phosphate	-
Tesla Model S (40 kWh)	EV	175	AC IM	40	Lithium nickel cobalt aluminium	Panasonic
Th!nk City	EV	37	AC IM	4.4	Zebra battery or lithium ion	A123 Systems
Toyota Prius PHV	PHEV	60	AC PMSM	4.4	Lithium nickel cobalt aluminium	Panasonic
Toyota RAV4 EV	EV	115	AC IM	41.8	Lithium nickel cobalt aluminium	Panasonic
Volvo C30 DRIVe Electric	EV	82	AC PMSM	24	Lithium nickel manganese cobalt	EnerDel
Wheego Whip	EV	45	AC IM	30	Lithium iron phosphate	Flux Power

Table 1: Electric motor and battery specifications for current generation electric vehicles on the market.

3. Battery Technology

The key component of any EV is the battery pack - ultimately determining an electric vehicle's maximum range, efficiency, charging time, lifespan and running costs. Current generation EV battery packs use lithium-ion cells with a specific energy of 100-180 Wh/kg, and which have expected lifespans of 10 years [10]. Although battery cells used in EVs typically cost around USD$400 per kWh, the cost per kWh for the entire battery pack is approximately USD$600 to 700 due to the additional control and thermal management systems. For a midrange EV such as the Nissan LEAF with a 24 kWh battery pack, this corresponds to an overall cost of USD$16,000 for the battery alone, or 30-40 per cent of its component cost [11, 12].

3.1. Battery Architecture

An automotive battery pack is composed of a large number of electrochemical cells, which are assembled into modules within the pack. For example, the Nissan LEAF battery pack is composed of 48 battery modules, each containing 4 lithium manganese spinel cells for a total of 192 cells, as shown in Fig. 2. Although the overall configuration and number of cells/modules varies between manufacturers, all battery packs are comprised of a large number of cells connected in series and parallel to produce sufficient voltage and current to power the electric drive [13, 14].

Each cell contains an anode and cathode, which vary depending on the battery chemistry, an electrolyte and a separator. The cells in turn are supported in plastic or metal supports to allow for modular assembly and to aid the integration of cooling systems. The integrated temperature control and cooling systems largely determine the physical construction of the battery pack, as required to ensure the temperature stability and safe operation of the cells.

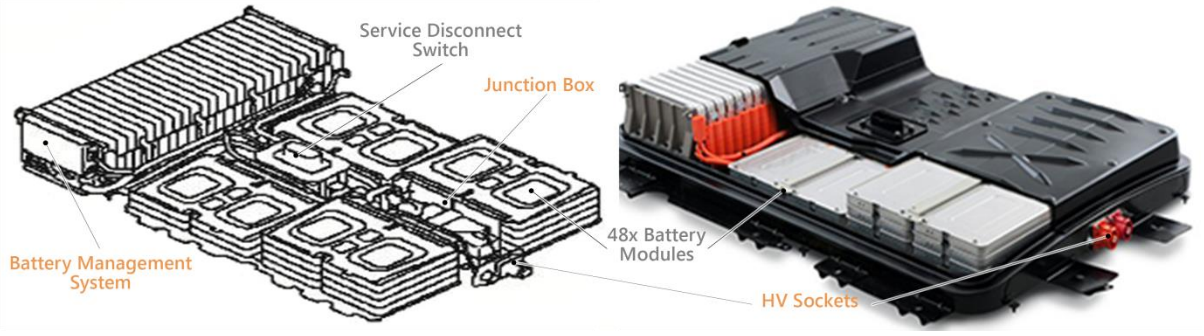


Figure 2. A diagram of the Nissan Leaf's battery pack highlighting the key components.

3.2. Battery Characteristics

Regardless of the type of EV there are six key characteristics that any battery must be evaluated against to be found suitable for use:

1) Specific energy
2) Specific power
3) Lifespan (calendar and cycle life)
4) Performance (temperature stability)
5) Cost
6) Safety

The key determinant for most automotive batteries is the specific energy – the amount of electrical energy stored per unit of mass (Wh/kg). It is the main quantity used to specify the capacity of a battery, determining the overall range of an EV for a specified drive efficiency. In practice compromises are often made to the battery size, with the specific energy being limited so as to maximise cycle life and thermal performance [12].

3.3. Battery Types

There are six main battery types that have been used in electric vehicles: lead acid, nickel cadmium, nickel-metal hydride, molten salt, lithium polymer and lithium-ion batteries. Lithium-ion (Li-ion) batteries are the main technology currently used for most consumer electronic and EV applications. Their success has largely been spurred by their high specific energy and power ratings as shown in Fig. 3, as well as excellent efficiency, internal resistance, life cycle and recharging characteristics. Although they have previously been hampered by high material costs and safety and thermal performance concerns, this is largely being addressed through expanding production volumes and the development of improved cell chemistries [15].

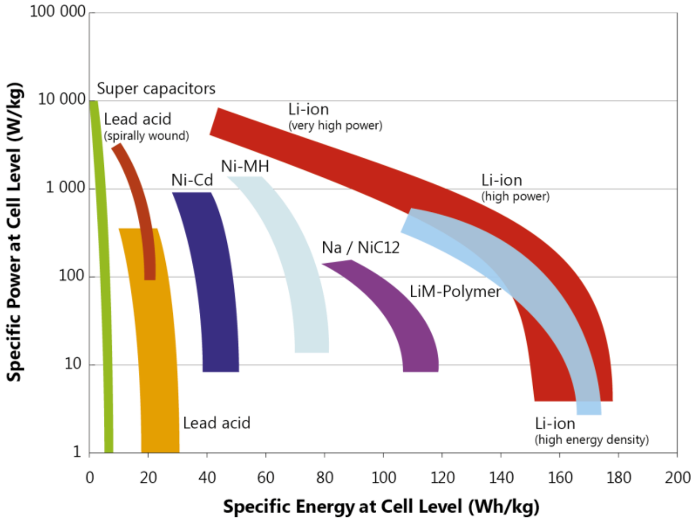


Figure 3. A Ragone chart depicting the range of specific energy and power levels achievable by current generation battery cell technology. Note that the specific energy and power of the final assembled battery pack will be lower than that of the constitutive cells [15].

3.4. Lithium-ion Battery Types

Different lithium-ion battery types or 'chemistries' contain different metal alloys in the cathode, and potentially different anode materials. These materials are selected to optimise key battery characteristics such as specific energy and charging performance. There are six alternative lithium-ion based chemistries that have been used, or are currently being used, in electric vehicles:

1) Lithium cobalt oxide (LCO)
2) Lithium nickel manganese cobalt (NMC)
3) Lithium nickel cobalt aluminium (NCA)
4) Lithium iron phosphate (LFP)
5) Lithium manganese spinel (LMO)
6) Lithium titanate oxide (LTO)

As shown in Fig. 4 there is no single lithium-ion chemistry that currently satisfies all of the requirements for an ideal EV battery. This has led to fragmented development and the adoption of different lithium-ion chemistries by vehicle manufacturers and OEMs, as outlined in Table 1. Although this situation is expected to persist in the short- to medium-term, it is predicted that NMC and NCA chemistries will be the focus of most future development and research interest due to their potential for higher specific energy levels [12].

3.5. Future Outlook

Current research and development for automotive batteries is concentrated on improving the specific energy of battery cells, thereby reducing the required battery size, weight and cost. In the short to medium term (2015-2020) it is expected that this will involve improvements to NMC and NCA chemistries, as well as the use of alternative high-capacity anodes such as silicon and lithium vanadium oxide in place of graphite. In addition, within this time frame it is predicted that average battery costs will drop by 50 to 60 per cent, from USD$800 to USD$320 as shown in Fig. 5. This will primarily be driven by decreasing raw material prices for the cathode, increased competition between electrolyte and electrode manufacturers, and increasing production volumes [11, 16].

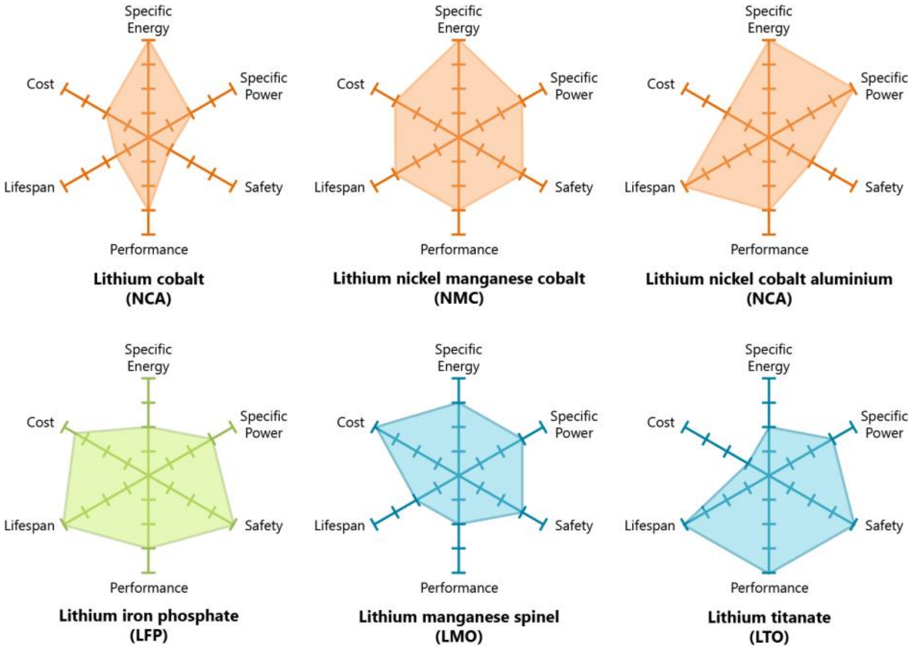


Figure 4. A comparison of lithium-ion chemistries used in electric vehicles. Note that the farther the chart extends along an axis the better the performance in that dimension (increasing specific energy and power, improved safety, higher performance, longer lifespan, and lower cost) [12].

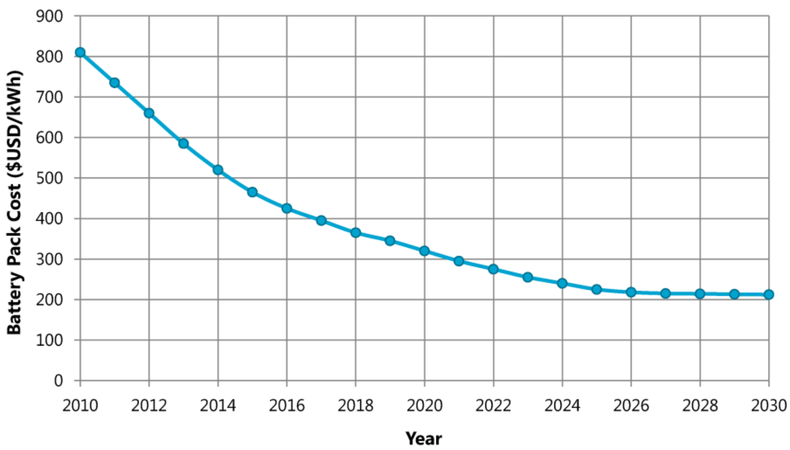


Figure 5. Estimated cost per kWh for a 30 kWh lithium-ion nickel metal cobalt battery pack [11].

In the longer term (2030 and beyond) alternative battery technologies such as metal-sulphur and metal-air may become viable alternatives to existing lithium chemistries. Both technologies have the potential for higher energy density than lithium batteries while using lower cost materials such as sulphur and zinc. In practice, the new technologies are expected to provide a specific energy of between 300 and 350 Wh/kg at a price point of USD$180 to USD$230 per kWh for a battery pack [11].

4. MOTOR TECHNOLOGY

The electric traction motor in an EV serves a dual role: to convert electrical energy supplied by the battery into mechanical energy for driving the transaxle, and to convert mechanical energy generated as the vehicle decelerates into electrical energy to charge the battery. However, a full EV's overall traction system is less mechanically complex than a traditional drive system in an ICV or HEV. This is aided by the fact that electric motors can instantly reach their maximum torque at low RPM and maintain it over the desired base speed range.

Above this base speed region, field weakening can be used to decrease motor torque and increase speed. This eliminates the need for a variable gear reduction system.

Consequently, electric motors can be used in traction applications with no or low fixed gearing. As the size of an electric traction motor largely depends on torque, a single fixed reduction gear is typically used to reduce motor volume and mass. The decreased mechanical coupling in turn increases the overall efficiency of the drive system and reduces the level of ongoing maintenance. High performance sports vehicles such as the Tesla Model S may still retain a variable gear system to increase the maximum speed range of the motor [17].

4.1. Motor Types

There are four main types of electric motor that have been incorporated into current generation EVs, as shown in Table 1, or that have been proposed for future EVs [18]:

1) Permanent Magnet Synchronous Motors (PMSM)
2) Induction/Asynchronous Motors (IM)
3) Hybrid Motors (HM)
4) Switched Reluctance Motor (SRM)

4.1.1. Permanent magnet synchronous motors

A permanent magnet synchronous motor (PMSM) is composed of a three-phase field winding in the stator, and permanent magnets mounted in the rotor. If the stator is driven by trapezoidal-shaped line currents it is called a brushless DC machine (BLDC). The shape of the current is determined by the winding of the stator coils, which are sinusoidally wound in PMSMs and evenly wound in BLDCs. While the majority of permanent magnet motors originally used in early electric vehicles were BLDC motors due to the simpler control scheme, they have largely been supplanted by PMSMs due to the decreased torque-ripple and higher efficiency levels.

As the permanent magnets generate significant magnetic flux without the need for rotor windings, PMSMs have higher peak efficiency than induction, switched reluctance and hybrid motors. PMSMs also benefit from a high torque-to-volume ratio and low inertia, resulting in a lower cost electrical machine that occupies less space. However, they suffer from a shorter constant power range due to the high constant air-gap field that is produced by the permanent magnets. In addition they depend on expensive rare earth metals such as neodymium for creating the strong permanent magnets [19].

4.1.2. Induction Motors

Induction motors (IMs) are currently the main motor technology competing with PMSMs in the EV manufacturing space. While PMSMs operate at a power factor near 1, induction motors used in EVs have a power factor of approximately 0.85. Thus, over the same speed range an induction motor will be less efficient. In addition, due to the current flowing in the rotor, an induction motor suffers higher peak efficiency losses and will generate more rotor heat.

Despite their lower efficiency and more complex control circuitry, EV manufacturers such as Tesla and Toyota are incorporating them in production-line EVs such as the Tesla Model S and Toyota RAV4 EV. This is primarily due to their lower cost, and concerns over the future supply of rare earth metals for permanent magnets. They also have a higher speed range due to the presence of rotor windings which allow the air-gap field to be weakened during high-speed operation [20, 7].

4.1.3. Hybrid Motors

Hybrid motors can be viewed as a combination of permanent magnet motors and induction motors, incorporating both permanent magnets and field windings into the rotor. The current in the rotor winding can be manipulated so as to weaken the air-gap field during high speed operation of the motor. This allows the output power of the motor to be reduced at higher speeds, increasing efficiency and allowing better control over the vehicle.

However, they have found only limited application in the EV manufacturing space due to the increased cost, complexity and resistive losses resulting from the added rotor windings. In particular, their low torque-to-speed ratio generally necessitates a multi-gear transmission system, which increases the overall motor cost, mechanical complexity and subsequent maintenance required [21].

4.1.4. Switched Reluctance Motors

Switched reluctance motors (SRMs) are a form of variable reluctance motor. The rotor does not contain permanent magnets or windings, but instead is made out of a ‘soft’ magnetic material such as laminated steel with a low coercivity. SRMs generally have relatively simple construction and control, and can operate over a longer constant power range during high-speed operation. Their main disadvantage is their significant torque ripple and associated noise problems, which has largely limited their application in commercial EVs [20].

4.2. Future Outlook

Permanent magnet synchronous motors are used in the majority of current generation EVs - a market dominance which is expected to continue for the foreseeable future. However, a future increase in the price of neodymium and dysprosium, or a decrease in market supply and availability, could lead to increasing use of induction motors. The focus of industry research and development will continue to be on improving the power density and efficiency of existing motors [22, 23].

5. INDUSTRY

5.1. Vehicle Manufacturers

In 2012 full electric and pluggable-hybrid electric vehicles comprised a relatively small proportion of total vehicle production. Despite a number of different EVs being developed and sold commercially by different manufacturers, General Motors, Toyota and Nissan combined currently hold almost 85 per cent of the EV market. While EV sales were dominated by full EVs in 2011, they were rapidly eclipsed by PHEVs in 2012 as shown in Table 2. This situation is expected to persist in the medium-term out to 2020 as consumers choose vehicles that are more fuel efficient, but which do not require them to sacrifice the range and refuelling convenience of traditional ICEs [24].

Manufacturer	EV Models	U.S. EV Sales (2012)
General Motors	Chevrolet Spark EV, Chevrolet Volt	23461
Toyota	Toyota Prius PHV, Toyota RAV4 EV	12942
Nissan	Nissan LEAF, Nissan Infiniti LE	9819
Ford	Ford C-Max Energi, Ford Focus EV	3059
Tesla	Tesla Model S	2650
BMW	BMW ActiveE, BMW i3	671
Mitsubishi	Mitsubishi i-MiEV	588
Honda	Honda Fit EV	93

Table 2. Main EV manufacturers and their total 2012 sales in the U.S. market [24].

5.2. *Battery Manufacturers*

There are a number of competing firms in the EV battery industry, each with alternative battery chemistries and different end markets. However, the market is largely dominated by joint ventures between energy or chemical companies and large vehicle manufacturers. Currently the top three manufacturers in the EV battery space are AESC (Automotive Energy Supply Corporation), LG Chem, and Panasonic Corp. which are closely associated with Nissan, General Motors and Ford, and Toyota respectively. These supply agreements allow vehicle manufacturers to leverage existing production capabilities for battery technologies, while also guaranteeing the long-term production volumes required for commercial stability. Alternatively, some companies such as BYD and Hitachi manufacture both their vehicles and batteries internally, allowing them to maintain complete control over the component supply chain [25, 13].

Due to the high-cost of battery production and uncertainty surrounding the market potential for EVs, the battery manufacturing industry remains relatively volatile. Smaller companies in the United States that produce predominantly automotive batteries, such as A123 and Valence Technology, have suffered financial issues despite significant government funding. The uncertainty in the EV market has led some firms to enter into marketing agreements with other battery manufacturers, or to specialise in niche end-use applications. Consequently, it is likely that the majority of automotive batteries will continue to be produced by well-established battery manufacturers in South Korea and Japan [26].

6. INFRASTRUCTURE

A range of infrastructure systems are required to support the introduction of any new transportation system. This includes roading, vehicle and part suppliers, vehicle testing and servicing, and refuelling networks. Specific to EVs is the need for high-power electric charging systems or ‘electric vehicle supply equipment’ (EVSE). To facilitate the wider uptake and acceptance of EVs these systems must be readily available, as well as being both safe and convenient to use. This is an important factor in alleviating range anxiety and encouraging frequent EV use [27].

6.1. *EV Charging Modes*

The International Electrotechnical Commission (IEC) has specified four different `modes' of EV charging in the IEC 62196 standard:

1) Mode 1 (Slow charge, non-dedicated socket)
2) Mode 2 (Slow charge, non-dedicated socket with protection)
3) Mode 3 (Slow-fast charge, dedicated socket)
4) Mode 4 (Fast charge, DC)

Most current generation EVs such as the Nissan LEAF, Chevrolet Volt and Tesla Model S supply portable charging cables that incorporate power control circuitry and pilot conductors. In the short- to medium-term, Mode 1 and 2 residential and business charging at 2.3 to 3.3 kW is expected to comprise the majority of vehicle charging events. This would allow an average 24 kWh EV to be fully charged in 6 to 8 hours [4].

6.2. *Grid Impact*

The greatest impact EVs are likely to have is on local grid infrastructure such as distribution lines and substations. In general, uptake of EVs is spatially clustered in certain areas - generally with a higher socioeconomic rating. This means that for a given city, substations in certain neighbourhoods may have to handle a disproportionate amount of the combined load from EV charging. In particular, if this peak EV demand coincides with the peak evening load as people arrive home it could lead to local substations exceeding their rated supply. Consequently, before any large scale adoption of EVs occurs, measures should be put in place to limit the degree of on-peak charging, or to incentivise off-peak charging [28, 29].

6.3. Future Outlook

In the medium-term it is expected that the majority of EV charging will be satisfied by Mode 1 EVSE in New Zealand. As the number of EVs in the fleet increases, Mode 1 and Mode 3 chargers will be introduced into vehicle-dense areas such as public and work car parks. This could occur in conjunction with free parking and/or charging schemes to encourage EV usage and uptake. Beyond 2020, as the charging performance of batteries increases and the cost of charging equipment decreases, Mode 4 chargers may be installed in increasing numbers.

Given the relatively low rates of current EV adoption, they are unlikely to have any noticeable impact on the grid over the medium-term. However, electric vehicle supply equipment and smart grid systems will be increasingly needed as EV numbers rise. Measures must also be taken to limit on-peak EV charging, either via a continuance of current night tariff schemes or, preferably, demand-side management via smart grid technology [29].

7. CONCLUSION

In conclusion, the key barrier to improved EV performance, lower costs and increased market uptake is their technology and, in particular, current generation lithium-ion batteries. Unless existing battery chemistries are further developed and specific energy, power and lifespan characteristics are improved, the range and overall life of electric vehicles will remain inferior to that of internal combustion vehicles. These developments are likely to occur through research by the leading battery technology manufacturers in South Korea and Japan. The actual integration of these battery systems and mass manufacturing of EVs will occur predominantly in the United States and Japan.

Consequently, in the short- to medium-term New Zealand will have wait for large manufacturers in other countries to increase EV production and decrease local prices through the economies of scale. However, New Zealand should start preparing now for the introduction of EVs. This includes the development of smart grid technology, increased renewable integration for charging, and real-world research into the potential of vehicle-to-grid technology for facilitating increased integration of these resources into the grid.

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